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Achromatic variability in the BL Lac Object PKS 2155-304. A case for microlensing?

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Abstract

PKS 2155-304 is the only BL Lac object for which well-sampled multiwavelength light curves resolve the intraday variability at UV and X-ray wavelengths. In particular we focus on the multifrequency campaign of November 1991, which showed a rather exceptional behaviour of the source exhibiting substantial achromatic variability from optical to X-ray wavelengths. We suggest a scenario for this unique event, where the variability is due to microlensing. The relativistic motion of the source relative to the lens is taken into account. The lenses are proposed to be solar-mass stars in an intervening dwarf galaxy. The a priori probability of detecting a microlensing event, however, was only few percent, small but not negligible.

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1 Introduction

BL Lac objects are Active Galactic Nuclei (AGN) in which most of the observed radiation likely comes from plasma moving relativistically toward the observer (Blandford & Rees 1978; Urry & Padovani 1995). This scenario explains characteristic blazar properties like rapid variability, high luminosities, and high polarization (Stein et al. 1976, Angel & Stockman 1980), as well as (to some extent) the low equivalent widths by which BL Lacs are defined (Morris et al. 1991, Stickel et al. 1991).

The most rapid variability has been resolved only for a handful of blazars that are bright enough or located in advantageous parts of the sky. For example, rapid intraday variability at radio and optical wavelengths has been observed in the BL Lac object PKS 0716+714 in part because of its high ecliptic latitude and therefore easy accessibility to dedicated radio and optical telescopes (Quirrenbach et al. 1989). At shorter wavelengths, very few blazars are bright enough to monitor with comparable temporal resolution. Only one or two can normally be observed with IUE at sub-one-hour integration times, and the brightest of these is PKS 2155-304.

Throughout November 1991, PKS 2155-304 was monitored daily with IUE, and for ~ 4.5 days in the middle of the month was observed nearly continuously with 90-minute resolution (see fig.3 of Urry et al. 1993). At roughly the same time, ~ 3.5 days of continuous Rosat observations were obtained (Brinkmann et al. 1994). The optical, UV, and X-ray light curves show strongly correlated variations with ~ 10 -30% amplitude over times scales of half a day to a day, with no dependence of amplitude on wavelength (Edelson et al. 1995). This achromatic variability is a rather unique behaviour of the

source during the observation under consideration and contrasts significantly, for instance, with the mode of variation detected during another long exposure performed in May 1994 (Urry et al. 1997). In terms of spectral shape, the optical through X-ray continuum from PKS 2155-304 can be understood as synchrotron emission from highly relativistic electrons (Urry & Mushotzky 1982), but achromatic variability of the kind observed in November 1991 is very difficult to explain as variations in the physical state of the synchrotron emitting plasma (Celotti et al. 1991).

In contrast, if the size of the emitting region is not a strong function of wavelength, at least for optical through X-ray wavelengths, then gravitational microlensing can cause achromatic variations, since the magnification itself is wavelength independent. For plausible lens parameters, intraday variability would result only if the relative source-lens velocity were relativistic but this occurs naturally in blazars assuming they have aligned relativistic jets. It has in fact been suggested that the BL Lac phenomenon may be explained by gravitational microlensing of Optically Violently Variable (OVV) quasars by foreground galaxies, wherein the low equivalent widths of BL Lacs relative to OVVs result from the compact continuum source being magnified relative to the extended emission line gas (Vietri & Ostriker 1983). Whether this microlensing scenario works for BL Lacs as a class is unclear (Urry & Padovani 1995) — but it may be important for individual objects (e.g., Stickel et al. 1993, Stocke, Wurtz & Perlman 1995).

In this paper we consider gravitational microlensing of a background relativistic source as a possible explanation for the rapid achromatic variability observed in PKS 2155-304. The effect of microlensing on source intensity

has already been studied in detail for quasars (Kayser et al. 1986, Schneider & Weiss 1987), and Krishna & Subramanian (1991) have developed the formalism for the case of relativistic source-lens velocities. Here, we review the basic equations, discuss the location of PKS 2155-304 and intervening matter, and make a quantitative assessment of whether microlensing can explain variability in this, the blazar with the best multiwavelength light curves.

2 Basic Lensing Theory

We consider the relevant equations for lensing, evaluating them numerically for the particular case of PKS 2155-304. Let D_S be the source-distance, D_L the lens-distance and D_{LS} the lens-source distance. The redshift of PKS 2155-304 is $z = 0.116$ (Falomo et al. 1993) and we adopt $D_S = 600$ Mpc (corresponding to $H_0 = 60$ km/s/Mpc, $q_0 = 0.5$). The two most likely locations for the lens are within the host galaxy of the BL Lac itself or at the intervening redshift, $z \sim 0.059$, at which strong Ly- α absorption has been seen in the far-UV spectrum of PKS 2155-304 (Bruhweiler et al. 1993).

2.1 Microlensing in a Central Stellar Cluster

As lenses we first consider stars in a stellar cluster which we suppose to be located at the center of the BL Lac host galaxy. We assume the cluster consists of $N = 10^7$ stars of mass $M = 1 M_\odot$ within a radius $R_L = 1$ pc. The radius of the Einstein ring for any one star is given by the classical equation

$$\xi = \sqrt{\frac{4GM}{c^2} \frac{D_L D_{LS}}{D_S}}. \quad (1)$$

Taking $D_{LS} \sim R_L = 1$ pc and $D_L \simeq D_S$, one gets $\xi = 1.4 \times 10^{12}$ cm, or roughly 2×10^{-10} arcsec. The optical depth to lensing is

$$\tau \simeq n\sigma R_L, \quad (2)$$

where n is the density of cluster stars. In the rough approximation of homogeneity,

$$n = \frac{N}{\frac{4}{3}\pi R_L^3} \quad (3)$$

and the lensing cross section is

$$\sigma = \pi\xi^2. \quad (4)$$

For the central stellar cluster we are considering, $\tau \sim 1.5 \times 10^{-6}$.

Now we further suppose that the source moves with a large tranverse velocity v_S in the source plane, large enough that it dominates over stellar velocities in the lens. One actually measures the angular velocity of the source, ω , converting to the transverse velocity at the source via $v_S = D_S\omega$. Here, however, the relevant velocity is the transverse velocity at the lens, $v_L = D_L\omega = \frac{D_L}{D_S}v_S$. The effective area that can activate the gravitational focusing in the lens plane is therefore

$$\Sigma_L \sim 2\xi \frac{D_L}{D_S} v_S t. \quad (5)$$

The time scale t for the occurrence of a lensing episode can be expressed through the condition

$$\Sigma_L n R_L = 1; \quad (6)$$

thus from Eqns. (3), (5), and (6), we have

$$t = \frac{2\pi R_L^2}{3v_S N \xi} \frac{D_S}{D_L}. \quad (7)$$

The typical duration of a microlensing episode, valid for small redshift of the source as in this case, is

$$T = \frac{\xi}{v_S} \frac{D_S}{D_L} . \quad (8)$$

(The correct expression in general is given by Eq. 5 in Krishna & Subramanian 1991.) Since we have taken as a typical length scale for the focusing the Einstein radius, the corresponding amplification factor is $\sim 30\%$ (e.g., Schneider et al. 1992).

Eqn. (8) is valid in the approximation of a point-like source, i.e., for source radius

$$R_S < \xi \frac{D_S}{D_L} . \quad (9)$$

When this approximation is not valid one should follow the treatment discussed by Schneider and Weiss (1987).

Since we are considering a BL Lac object, the apparent source velocity at us or at the lens is likely relativistic (Vermeulen & Cohen 1994) and we adopt a bulk Lorentz factor $\gamma = 5$. Moreover, we assume the viewing angle to be small, with a representative value $\theta = 10^\circ$, which results in an apparent transverse velocity $v_S = 5c$.

For this choice of parameters Eqns. (7) and (8) yield: $t \sim 110$ days, $T \sim 9$ s, which is far too rapid for the observed variations. This remains true for other plausible locations of stellar clusters in the host galaxy and so we turn to lenses not associated with the host galaxy.

2.2 Microlensing by an Intervening Dwarf Galaxy

In the particular case of PKS 2155-304, there is a high probability that stars could be located along the line-of-sight, approximately halfway to the BL

Lac object. This is because ultraviolet spectra of PKS 2155-304 exhibit Ly- α absorption features at $z = 0.057$, 0.059 , and 0.060 . The $z = 0.059$ system is particularly strong, with equivalent width $W_\lambda \sim 1 \text{ \AA}$ (Maraschi et al. 1988, Allen et al. 1993, Bruhweiler et al. 1993, Appenzeller et al. 1995). The nature of the absorber is unknown since no associated metal lines have yet been detected, and because the Ly- α line is unresolved, the hydrogen column density is indeterminate. Optical images with a seeing ≤ 1 arcsec indicate no foreground galaxies brighter than $m_V = 19$ within 7 arcmin of the source (Falomo et al. 1993). If the absorber is a galaxy and not a hydrogen cloud, it must be a dwarf galaxy very close to the line of sight to PKS 2155-304.

Following this scenario, the lens distance is $D_L = 300 \text{ Mpc} \simeq D_{LS}$, the lens radius is $R_L = 1 \text{ kpc}$, and we assume the central part of the dwarf galaxy contains $N = 10^9$ stars of mass $1 M_\odot$. Using Eqns. (1), (7), and (8), we get (with $M = 1 M_\odot$) $\xi = 5.4 \times 10^{-3} \text{ pc} = 1.66 \times 10^{16} \text{ cm}$, $t = 185 \text{ d}$, and $T = 2.6 \text{ d}$. The duration is the right order of magnitude, especially given the crude approximations used to derive Eqns. 7 and 8.

3 Discussion

BL Lacs are likely characterized by the relativistic bulk motion of their emission regions. As is apparent from Eqns. (7) and (8), this implies a drastic reduction of the recurrence time and of the duration of the lensing episodes relative to conventional microlensing of quasars. Indeed, the time scales for microlensing considered here range from a few seconds for a central stellar cluster in the BL Lac host galaxy to a few days for stars in an intervening galaxy.

In practice, an episode with the characteristics corresponding to lensing by a central stellar cluster would be rather hard to detect because of its short duration, and it certainly does not correspond to the variations seen in November 1991. Furthermore, the condition on the source size (Eqn. 9) implies an unreasonably small size of the optical/UV/X-ray emitting region in PKS 2155-304, $R_S < 10^{12}$ cm.

In contrast, the time scale for microlensing by a stellar cluster in a galaxy at $z = 0.059$, the redshift of a known Ly- α absorption system along the line-of-sight to PKS 2155-304, is the right order of magnitude for the observed November 1991 light curve. In this case, also, Eqn. 9 implies a reasonable limit on the size of the optical/UV/X-ray emitting region in PKS 2155-304, $R_S < 3 \times 10^{16}$ cm, easily commensurate with our understanding of the emission mechanism in this BL Lac object.

As discussed by Urry et al. (1993) the flux variation is essentially achromatic. On this regard see also Brinkmann et al. (1994, figs. 3 and 6) for the X-ray observations and Edelson et al. (1995, fig. 2b) for a comparison of optical, UV and X-ray light curves. The overall duration of the event is ~ 4 days. The spiky structure apparent in the light curves may be related to the caustic web as discussed by Schneider & Weiss (1987) and Krishna & Subramanian (1991) and/or to a structure of the relativistic blobs. Moreover, one should consider that the source is certainly variable independently of microlensing and the light curve could represent the superposition of the two processes.

One concern is that microlensing events should be quite rare, raising a question as to the probability of our having observed the phenomenon.

Specifically, with a recurrence period of 185 days, a campaign lasting ~ 5 days (as in November 1991) should detect microlensing events only a few percent of the time, a very small though non-negligible fraction. A slightly longer monitoring campaign in May 1994 did not reveal similar low-amplitude, achromatic variability — indeed the wavelength dependence of the variability was quite dramatic (Urry et al. 1997) — but we are clearly dealing with small-number statistics. (These two sets of observations represent the only data with which rapid UV/X-ray variations could have been resolved.)

Another problem for establishing the importance of gravitational microlensing in PKS 2155-304 is, as we already noticed, that different variability mechanisms are certainly at work, as demonstrated by the contrast between the achromatic variations in November 1991 and the strong spectral variability seen in May 1994. Thus the possibility of confusion among different kinds of variations exists.

Nevertheless, we have demonstrated that microlensing by stars in a dwarf galaxy at the known redshift of Ly- α absorption toward PKS 2155-304 is a promising scenario for explaining its rapid, correlated, achromatic, optical/UV/X-ray variability. The clearest proof of the validity of this hypothesis would be the detection of the dwarf galaxy itself; however, given the brightness of the BL Lac nucleus, this will be difficult even with HST.

Whether microlensing is an important source of variability in other BL Lacs remains to be seen. Two likely prerequisites, following from our discussion of PKS 2155-304, are that the observed multiwavelength variability be at least roughly achromatic (well-correlated with lag smaller than a few hours) and that there is some evidence for intervening matter along the line of sight.

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